Performance of orbital remote sensing in the detection of landslides in southwest Coastal British Columbia.

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EXECUTIVE SUMMARY

The utility of satellite imagery for landslide detection in southwest coastal British Columbia was evaluated by interpretation of orbital imagery (SPOT, IKONOS, and QUICKBIRD) and comparison with large- and medium-scale aerial photography. Satellite imagery was enhanced by simple, repeatable digital image processing techniques (contrast stretches and transformations, merging of images of different spatial resolutions, composition of 3-band composite images, and band ratioing). More numerous processing options were available for IKONOS and QUICKBIRD imagery than for SPOT due to the multispectral nature of the former.

Examples of satellite imagery are provided to demonstrate detection of obvious, small, and relict landslides, identification of detail on large landslides, and interpretation problems caused by topographic shadows. Approximations of the smallest landslides visible under ideal illumination and viewing conditions were 1700 m^2 for 5 m SPOT panchromatic imagery, 1000 m^2 for 2.5 m SPOT panchromatic imagery, and 175 m^2 for panchromatic-sharpened multispectral IKONOS and QUICKBIRD imagery. Insufficient perception of morphology at these sizes, however, prevents absolute identification of the features as landslides. In the absence of stereoviewing, greater minimum landslide sizes than those indicated above for detection are required for landslide identification. The exact landslide size varies with illumination conditions, viewing geometry, and contrast between the landslide and the surrounding terrain. Detail visible on IKONOS and QUICKBIRD imagery of large landslides included large debris blocks and gullies on slope surfaces. Relict landslides were identifiable on multispectral imagery mainly due to increased green and near infrared spectral reflectance of colonizing vegetation. Topographic shadowing was found to hinder landslide interpretation on both aerial photographs and satellite imagery. This problem was severe for SPOT panchromatic imagery, but was slightly reduced by image contrast transformation. Shadow problems were significantly reduced on IKONOS and QUICKBIRD imagery by band ratioing using the red and near infrared bands.

Some considerations important in landslide detection using remotely sensed imagery are also discussed. Re-vegetation masks landslides and can prevent detection of landslides where significant time has passed between time of failure and time of imaging. One of the most important factors affecting the ability of a sensor to detect landslides is spatial resolution. All other conditions being equal, the minimum size of a feature detectable from remotely sensed imagery decreases as spatial resolution increases. As sensor resolution increases, however, the area covered by a single image decreases, reducing the synoptic coverage provided by the imagery.

Based on interpretation of satellite imagery and aerial photography for landslide detection and supported by the provided examples, several conclusions are made:

- High spatial resolution, multi-spectral data collection, and stereoscopic viewing greatly improve the ability of a sensor for landslide detection.
- IKONOS and QUICKBIRD imagery out-performed SPOT imagery for landslide detection.
- The processed images allowing for optimal interpretation of IKONOS and QUICKBIRD scenes are colour infrared composites and band ratioed images.
- Despite multispectral imaging and high spatial resolution (relative to other satellites) IKONOS and QUICKBIRD did not allow delineation of all landslides visible on large-scale aerial photographs.

- Increased aerial coverage provided by satellite images (relative to a single aerial photograph) improves ease of imagery reconnaissance.

Recommendations for future evaluation of remotely sensed imagery for landslide detection include:

- Imagery used for landslide detection should combine three properties: high spatial resolution, multi-spectral data collection, and stereoscopic viewing.
- A multi-scale approach to landslide investigations using satellite imagery and aerial photography could be used.
- Ground truthing and quantitative accuracy assessment should be performed.
- When evaluating the use of more than one sensor for landslide detection, imagery should be acquired over the same area and under the same imaging conditions.
- Imagery should be acquired in or converted to a digital format.
- If detailed spatial measurements are to be reliably derived form satellite data, metric accuracy of the sensor must first be evaluated.
- Successful methods should be replicated in other study areas.

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1 INTRODUCTION

Landslides are a common occurrence in many areas of southwest coastal British Columbia because of the steep topography and high annual precipitation in this region. The already high landslide risk is increased in many areas by timber harvesting. An improved understanding of landslides and the degree to which they are influenced by timber harvest is required to evaluate and reduce impacts on resources (e.g. property, timber, water, wildlife).

Evaluation of landslides in southwest coastal British Columbia is complicated by the inaccessibility of many areas and the vastness of areas affected by landslides. Remote sensing is well suited to the inventory and study of landslides in southwest coastal British Columbia through its ability to collect spatially continuous data over geographically large areas. Consequently, many studies of landslides utilise remote sensing. One such project is the evaluation of "Management of Landslide Hazard under the British Columbia Forest Practises Code," currently being conducted by the Forest Practices Board(Chatwin 2004). Identification and characterisation of landslides is required two objectives outlined in this project (Chatwin 2004):

1) to "determine the incidence of landslides in harvested areas and their resource impacts," and
2) to "determine how well terrain stability mapping and field assessments predict the likelihood and character of landslides following logging and road building."

Interpretation of landslides from remotely sensed imagery can aid in addressing both of these objectives.

Imagery from three orbital sensors (SPOT, IKONOS, and QUICKBIRD) has been obtained for areas on Vancouver Island. Although several reports (Collins et al. 2001; Collins and Kliparchuk 2004; Kliparchuk and Collins 2003) have considered IKONOS and QUICKBIRD imagery for resource management purposes, no detailed assessment of these sensors for landslide detection has been performed. In addition, no published literature assessing high (> 5 metre) resolution orbital sensors for landslide detection is currently available. This report discusses the utility of SPOT, IKONOS, and QUICKBIRD for landslide detection in southwest coastal British Columbia. Some considerations necessary during compilation of landslide inventories from high resolution satellite imagery are also discussed.

2 METHODOLOGY

2.1 STUDY AREA:

Figure 1 shows the location of the four satellite scenes assessed in this report. The imagery covers three geographical areas with overlap occurring only between the IKONOS and QUICKBIRD scenes (Figure 1). Other moderate- to high-resolution satellite imagery has been obtained over Vancouver Island and the adjacent mainland coast, but is not discussed here and is not, therefore, shown in Figure 1.

2.2 INDICATORS USED IN LANDSLIDE DETECTION

Landslide detection using remotely sensed imagery relies on differentiation between the surface properties of landslides and the surrounding terrain. Climatic conditions in most parts of

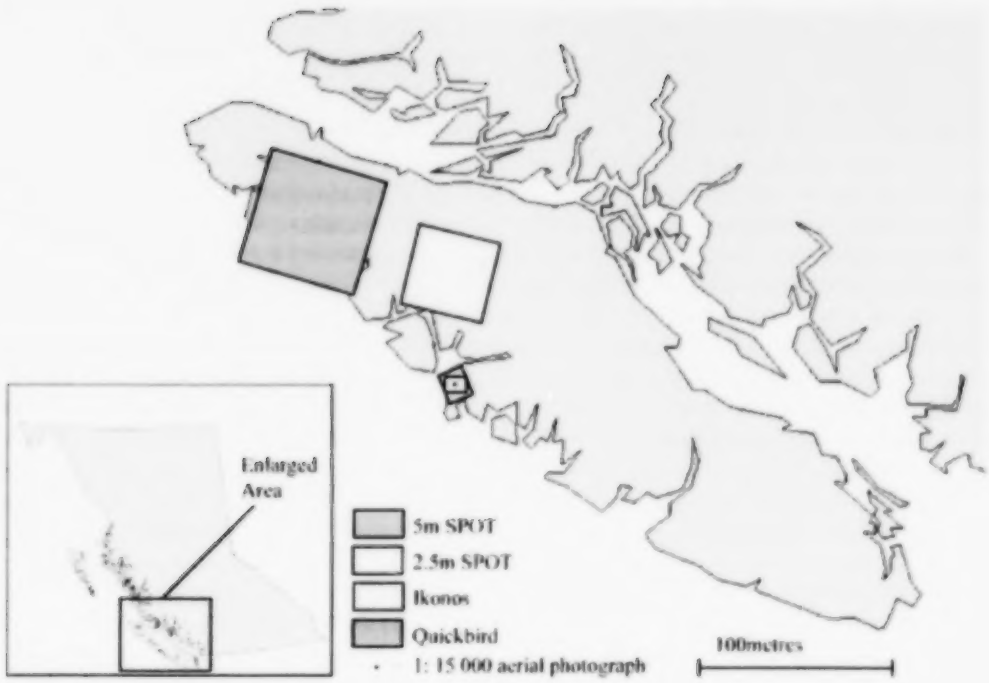

Figure 1: Locations of satellite scenes.

southwest coastal British Columbia, including the study area considered here, result in vigorous vegetation growth. Bare ground surfaces (e.g. soil, rock) have distinctly different reflectance and textural properties than vegetation, allowing separation between these surface types. Disturbance or removal of vegetation can, therefore, be used as a landslide indicator on remotely sensed imagery of southwest coastal British Columbia. Other information, such as feature morphology, is required to differentiate bare ground surfaces caused by landsliding from those resulting from other processes.

2.3 IMAGERY:

Table 1 lists basic information about each of the scenes shown in Figure 1. None of these scenes provide stereoscopic coverage. Large-scale (1: 15 000 and 1: 40 000) aerial photographs were obtained for selected areas covered by each of the satellite scenes. Aerial photography was used both for reference during interpretation and for qualitative evaluation of processed satellite imagery. Details of the aerial photographs used are provided in Table 2.

2.4 IMAGE PROCESSING:

For all imagery, the only pre-processing was conducted only by image suppliers. Subsequent radiometric and geometric corrections were not made. Prior to image processing the dynamic ranges of all images were clipped and linearly stretched to an 8-bit scale. As a result, each band was normalised to a range of 0 to 255. All image processing was conducted using ER Mapper® 6.4 (Earth Resource Mapping 2004).

Table 1: Details of satellite scenes shown in Figure 1.

Sensor	Spectral Resolution	Spatial Resolution (m)	View Angle	Acquisition	
				Date	Time
SPOT	Panchromatic	5.0	1.5°	September 1, 2003	19:44
	Panchromatic	2.5	7.8°	November 3, 2003	19:32
Ikonos	Panchromatic Multispectral	1.0 4.0	29.8°	September 21, 2000	19:16
Quickbird	Panchromatic Multispectral	0.61 2.44	-*	September 4, 2003	-*

* Metadata not available.

Table 2: Details of aerial photography.

Flight Line	Film Emulsion	Approximate Scale	Acquisition		Corresponding Satellite Scene
			Date	Approx. Time	
15BCB96017	Black & white	1:40 000	July 26, 1996	10:30	5m SPOT
30BCC98009	Colour	1:15 000	July 21, 1998	13:00	
15BCB96096	Black & white	1:40 000	September 23, 1996	11:30	2.5m SPOT
30BCB95036	Black & white	1:15 000	June 21, 1995	19:32	
30BCC98010	Colour	1:15 000	July 22, 1998	16:00	Ikonos and Quickbird

2.4.1 *SPOT Processing*

Enhancement techniques that can be applied to SPOT imagery evaluated here are limited to contrast enhancements because SPOT images considered here are panchromatic (Table 1). Two transformations were applied to improve contrast between vegetated and un-vegetated ground. Linear contrast stretches and logarithmic contrast transformations were applied to enhance landslides in sunlit and shadowed portions of the imagery, respectively.

2.4.2 *IKONOS and QUICKBIRD Processing*

Various images were considered for each IKONOS and QUICKBIRD. These included:

- Single bands.
- Three-band colour and colour infrared composites.
- Band ratios.

Band ratioing decreases the effects of variation in illumination by considering relative reflectance differences in two bands. Six band ratios (e.g. all combinations possible for a four-band image) were assessed. In the case of three-band composites, panchromatic and multispectral datasets were merged to produce "pan-sharpened" images. Linear contrast stretches were applied to single bands, band ratios, and each band of the three-band composites.

2.5 Interpretation:

Landslides were identified by manual interpretation of processed imagery. Numerous landslides were easily identifiable from the IKONOS and QUICKBIRD images due to the high resolution of these sensors and the abundance of landslides in the area covered by the selected scenes. Features from aerial photographs were not required to train interpretation. Landslides recognition on SPOT was complicated by the lower spatial and spectral resolutions of this sensor. Known landslides identified from large-scale aerial photographs were used to train visual interpretation of SPOT imagery. Interpretation was conducted for the entire 2.5 m SPOT scene. Due to time constraints, only a small portion of the 5 m SPOT scene was interpreted.

The properties used in the recognition of landslides were:

- Textural pattern.
- Spectral/radiometric characteristics.
- Topographic relationships.

Selected regions of interpreted images were qualitatively compared to aerial photographs. Neither ground truthing nor a quantitative assessment of accuracy was completed for the satellite images.

3 RESULTS AND DISCUSSION

3.1 Performance of Processed Imagery

General performance of processing methods for landslide detection is discussed below. Examples of imagery performance are given in section 3.2.

3.1.1 *Performance of SPOT Imagery*

The recognition of landslides in sunlit areas was improved by linear contrast stretching, maximized contrast between vegetated and un-vegetated ground on sunlit slopes. Landslides on shadowed slopes were not, however, visible on these images. Improved recognition of landslides in shadow areas was achieved by logarithmic contrast transformation. Logarithmic contrast transformation preferentially lightens dark portions of an image (e.g. shaded slopes), although some lightening also occurs in already light portions of the image (e.g. sunlit slopes). Logarithmic contrast transformation reduced contrast between landslides and adjacent terrain on sunlit slopes. Consequently, viewing of both images (linear contrast stretched and logarithmic contrast transformed) was required for landslide detection.

3.1.2 *Performance of IKONOS and QUICKBIRD Imagery*

The greater spatial and spectral resolution of the IKONOS and QUICKBIRD satellites, relative to SPOT, greatly improved landslide detection. Landslide detection with true colour composites was still, however, difficult on shadowed slopes. For each sensor, the three visible bands are highly correlated and, therefore, provide similar distinction between vegetated and un-vegetated ground. The relative reflectance characteristics of vegetated and un-vegetated ground in the near infrared portion of the electromagnetic spectrum are very different to those in the visible parts of the spectrum. Consequently, the infrared band of IKONOS and QUICKBIRD provides spectral information not available from the visible bands of these sensors.

Combination of visible and infrared bands, either as a false colour (e.g. colour infrared) composite or band ratio, increased contrast between vegetated and un-vegetated ground, and improved landslide detection. Colour infrared composites enhanced landslide recognition relative to normal colour composites while maintaining textural information present in colour composites. The ratio Red/IR was found to be the most useful ratio for landslide detection. This ratio maximizes contrast between vegetated and un-vegetated ground, and reduces the effects of topographic shadows. Other information in the ratioed image (e.g. texture of vegetation) is, however, lost.

Pan-sharpened images combine the increased spatial resolution of textural information offered by the panchromatic band with multispectral information offered by the visible and near infrared bands. Figure 2 shows a normal colour IKONOS scene without (Figure 2a) and with (Figure 2b and 2c) addition of the panchromatic band. Pan-sharpening increased the apparent spatial resolution of the merged dataset (Figure 2b). Intensity differences between sunlit and shaded slopes are, however, significantly increased because of the sensitivity of this band to variation in illumination. This sensitivity results from the broad bandwidth of the panchromatic band and reduces interpretability of features in shadows. Lightening of the panchromatic band was used to reduce shadow effects in the pan-sharpened image. Lightening of the panchromatic band was achieved by contrast manipulation and reduced perception of features in shadows, although the perception of increased spatial resolution in the pan-sharpened image is also reduced (Figure 2c). This method was applied to all normal colour and colour infrared images used for interpretation. Panchromatic bands of all subsequent pan-sharpened IKONOS and QUICKBIRD images shown in this report have been lightened.

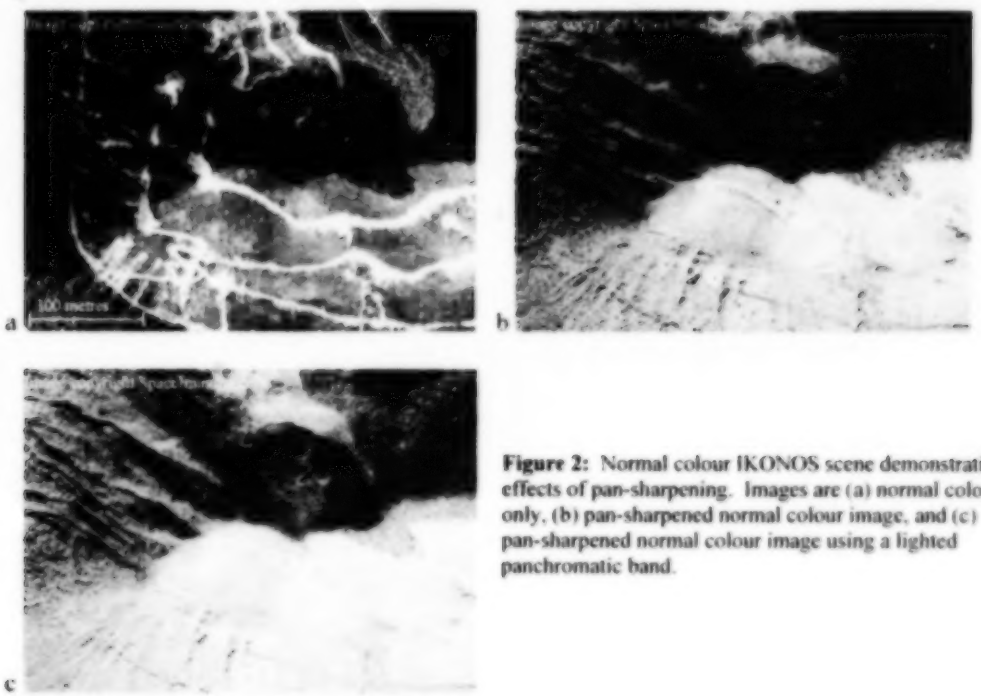

Figure 2: Normal colour IKONOS scene demonstrating effects of pan-sharpening. Images are (a) normal colour only, (b) pan-sharpened normal colour image, and (c) pan-sharpened normal colour image using a lighted panchromatic band.

3.2 Examples of Landslide Detection

3.2.1 *Obvious Landslides*

Obvious landslides are visible in all four scenes considered. The ease with which landslides are detectable depends on both characteristics of the landslide (e.g. size and contrast with surrounding terrain) and the sensor used (e.g. spatial and spectral resolution). Size and contrast with surrounding terrain are the most important characteristics of landslides, with large landslides and landslides surrounded by undisturbed vegetation (e.g. natural landslides) being the most noticeable. Figure 3 shows large natural landslides in a 5 m SPOT panchromatic scene. These landslides are easily discernable from the surrounding vegetated terrain.

Figure 4 shows a number of obvious landslides in a QUICKBIRD scene and demonstrates the benefit of increased spectral resolution in landslide detection. Recognition of the landslides increases from the panchromatic image (Figure 4a) to the true colour image (Figure 4b), and from the true colour image to the colour infrared image (Figure 4c). The increased number of landslides visible in the QUICKBIRD scene (Figure 4) relative to the SPOT scene (Figure 3) is a result of a greater spatial frequency of landslides in the area covered by the QUICKBIRD scene. The influence of spatial resolution on landslide detection is demonstrated in section 3.3.1.

3.2.2 *Small Landslides*

Below a minimum size, landslides are no longer detectable by remote sensing. This size is a function of sensor resolution and the contrast between the landslide and adjacent terrain. Figure 5 is a 5 m SPOT panchromatic scene enhanced by both linear contrast stretching and logarithmic contrast transformation (Figures 5a and 5b, respectively) showing numerous landslides. The same area on a 1: 40 000 black and white aerial photograph is shown for comparison (Figure 5c). On a sunlit slope a landslide (I – approximate area 6000 m^2) is clearly visible on both the SPOT images. A landslide of similar size on a shaded slope (II – approximate area 5000 m^2) is not visible on either the linear contrast stretched or logarithmic contrast transformed SPOT image. A small landslide (III – approximate area 1700 m^2) is detectable on a sunlit slope. Another small landslide of similar size (IV – approximate area 1700 m^2) is visible on both the SPOT images (Figure 5a and 5b), but is not recognizable as a landslide. Confirmation that this feature is a landslide required stereoscopic interpretation of a 1: 40 000 black and white aerial photographs.

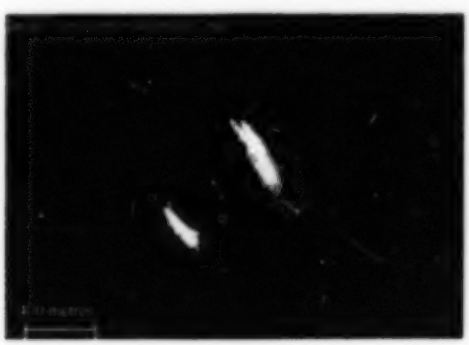

Figure 3: 5 m SPOT panchromatic scene showing obvious large natural landslides.

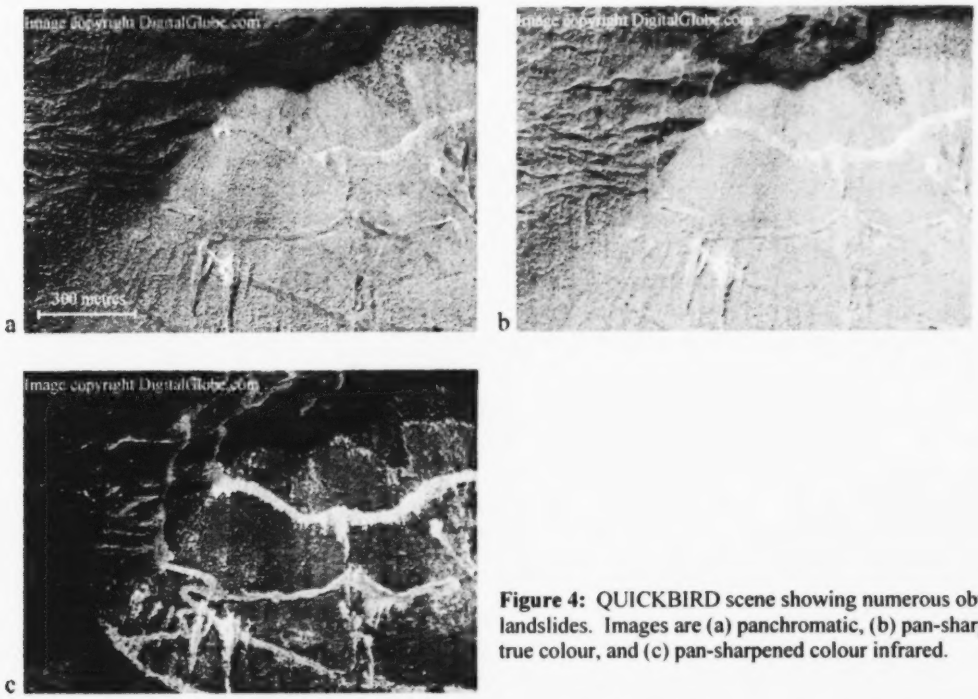

Figure 4: QUICKBIRD scene showing numerous obvious landslides. Images are (a) panchromatic, (b) pan-sharpened true colour, and (c) pan-sharpened colour infrared.

Figure 6 is a 5 m SPOT panchromatic scene enhanced by both linear contrast stretching and logarithmic contrast transformation (Figures 6a and 6b, respectively) showing numerous landslides. The same area on a 1: 40 000 black and white aerial photograph is shown for comparison (Figure 6c). A landslide in a gulley partially obscured by topographic shadow (I – approximate area 2700 m^2) is clearly identifiable in both the linear contrast stretched and logarithmic contrast transformed images. Another landslide occurring completely within a shaded area of the image (II – approximate area 1600 m^2) is not detectable. This landslide shows no contrast difference with the surrounding terrain in the linear contrast stretched image (Figure 6a). In the logarithmic contrast transformed image (Figure 6b) this landslide is only slightly lighter than the surrounding terrain and, without perception of three-dimensional morphology, cannot be recognized as a landslide. In both the linear and logarithmic contrast transformed images a small landslide on a sunlit slope (III – approximately 1000 m^2) is visible, but is not recognizable as a landslide due to a lack or morphological expression.

Landslides on sunlit slopes at least as small as 1700 m^2 can be detected from 5 m SPOT panchromatic imagery. The minimum size of landslide that can be detected from 2.5 m SPOT imagery is above 1000 m^2. On shaded slopes, however, even very large landslides may not be detectable. Detection of landslides also depends on the expression of feature morphology in both two- and three-dimensions.

Figures 7 and 8 show a small landslide (L – approximate area 175 m^2) barely detected by IKONOS and QUICKBIRD, respectively. This landslide is not visible in pan-sharpened true colour images (Figure 7a and 8a), but the landslide is detectable in pan-sharpened colour infrared images (Figures 7b and 8b) due to increased contrast between vegetated and un-vegetated ground. This landslide occurs under ideal detection conditions; the slope is directly illuminated

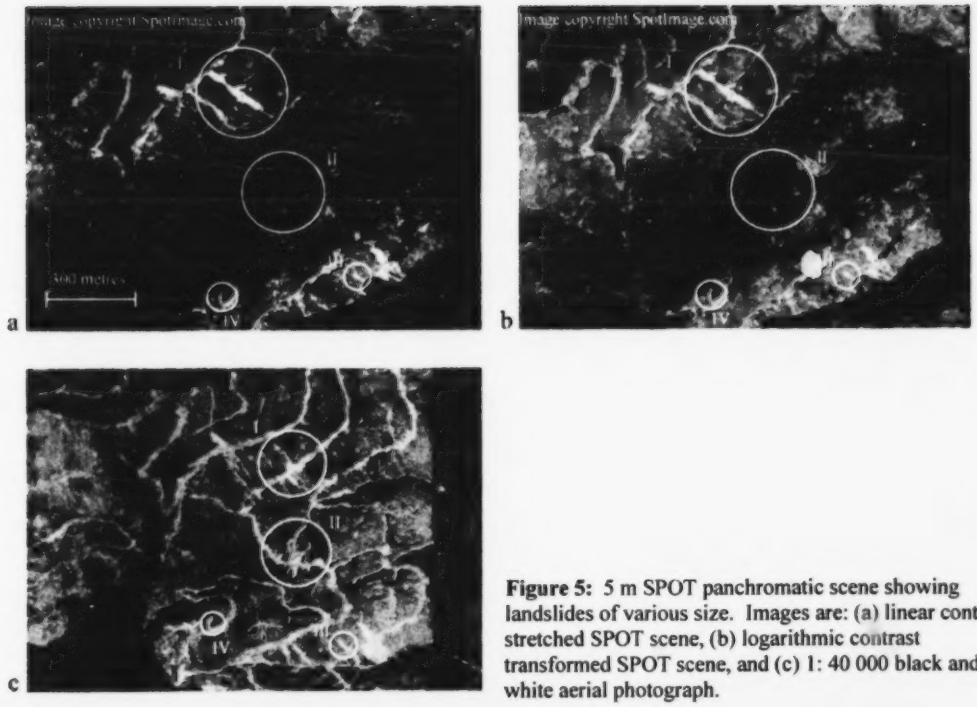

Figure 5: 5 m SPOT panchromatic scene showing landslides of various size. Images are: (a) linear contrast stretched SPOT scene, (b) logarithmic contrast transformed SPOT scene, and (c) 1: 40 000 black and white aerial photograph.

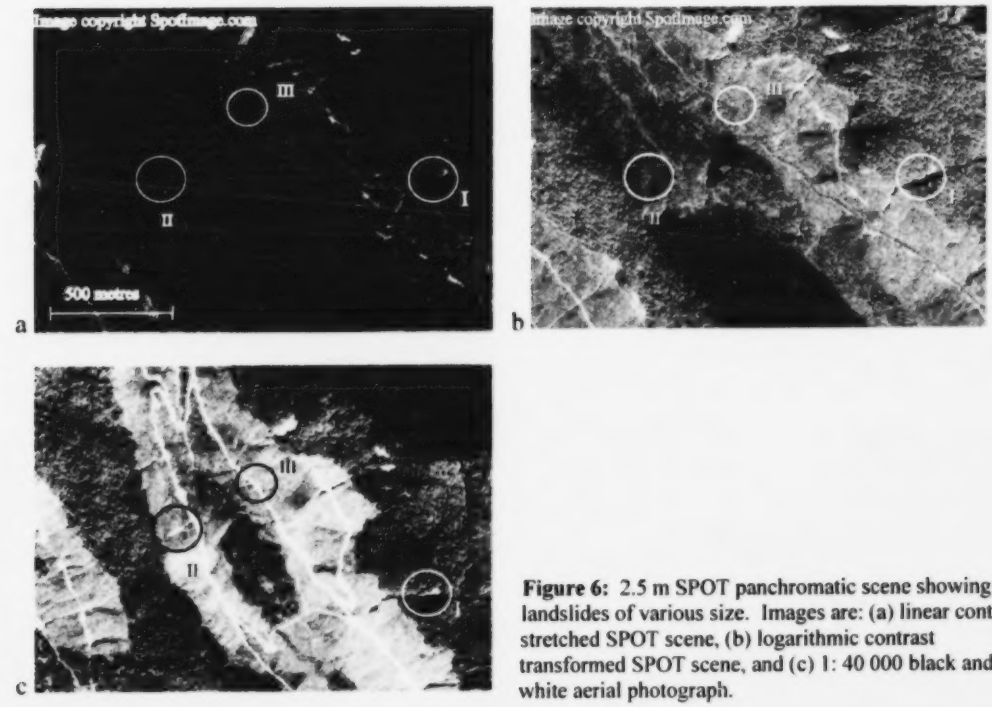

Figure 6: 2.5 m SPOT panchromatic scene showing landslides of various size. Images are: (a) linear contrast stretched SPOT scene, (b) logarithmic contrast transformed SPOT scene, and (c) 1: 40 000 black and white aerial photograph.

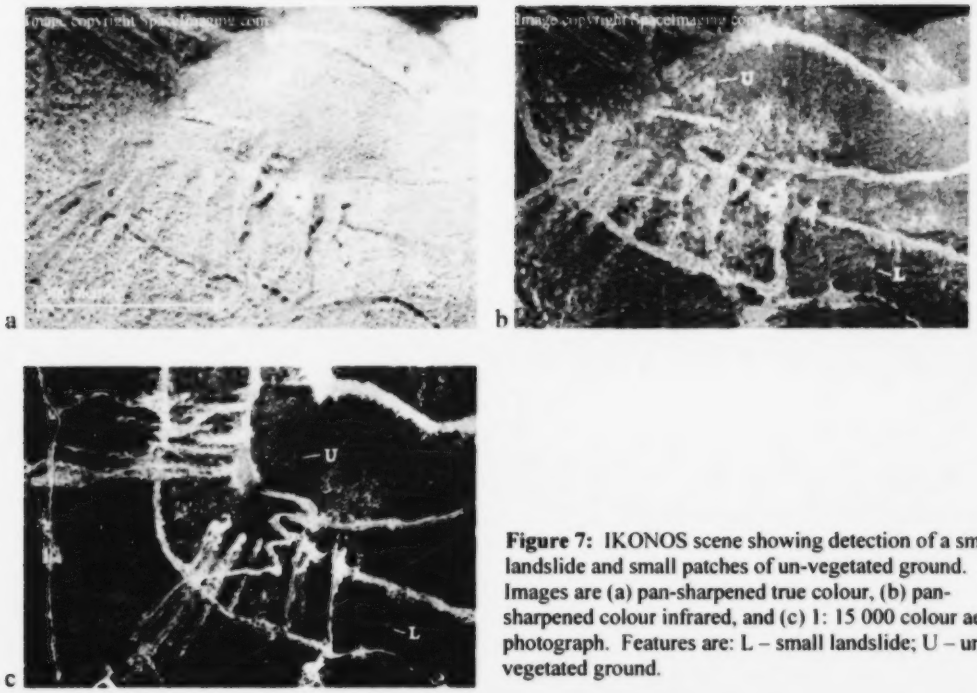

Figure 7: IKONOS scene showing detection of a small landslide and small patches of un-vegetated ground. Images are (a) pan-sharpened true colour, (b) pan-sharpened colour infrared, and (c) 1: 15 000 colour aerial photograph. Features are: L – small landslide; U – un-vegetated ground.

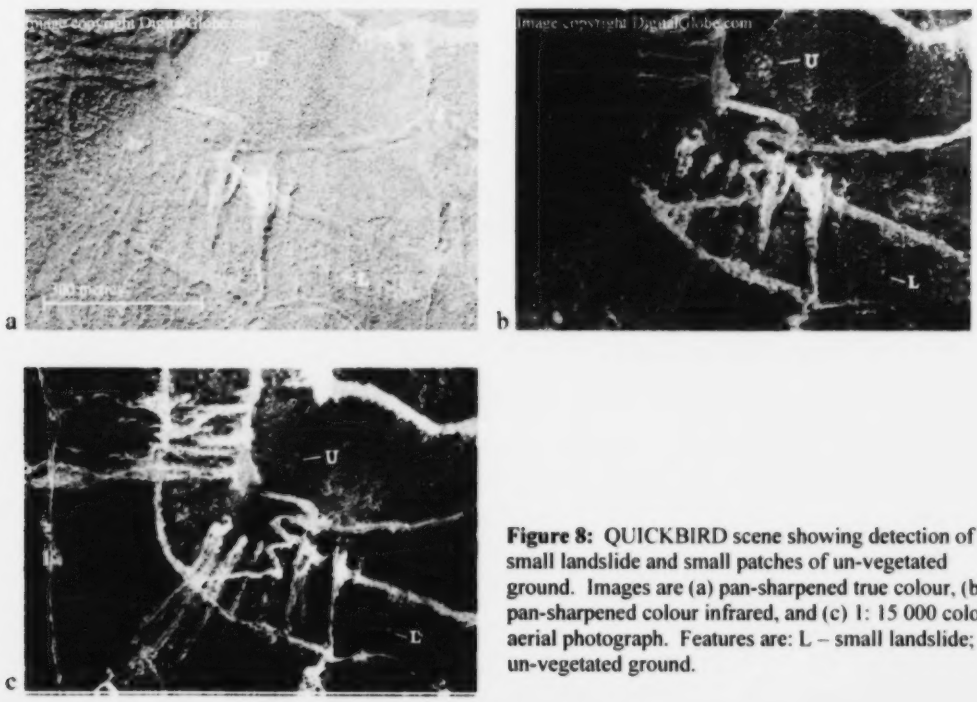

Figure 8: QUICKBIRD scene showing detection of a small landslide and small patches of un-vegetated ground. Images are (a) pan-sharpened true colour, (b) pan-sharpened colour infrared, and (c) 1: 15 000 colour aerial photograph. Features are: L – small landslide; U – un-vegetated ground.

and has an aspect facing the look angle of the sensor. Under less favourable conditions (e.g. shadowed slopes, or aspects not oriented directly toward the look direction of the sensor) it is unlikely that a landslide of this size would be detectable. It should be noted that, although this landslide is detectable on the IKONOS and QUICKBIRD images, in cannot be accurately identified as a landslide due to a lack of morphology conveyed by the imagery. Confirmation that this feature was indeed a landslide required reference to large-scale stereoscopic aerial photography, which provides stereoviewing and sufficient spatial resolution to perceive both 2-dimensional and 3-dimensional morphology.

In the absence of sufficient spatial resolution (to allow perception of 2-dimensionsal morphology) and stereoscopic coverage (to allow perception of 3-dimensional morphology) confusion does occur between small landslides and other un-vegetated features. This is evident in Figures 7b and 8b, where small un-vegetated areas (U) appear very similar to the small landslide (L). These un-vegetated areas were determined to not be landslides based on stereoscopic aerial photographic interpretation. The un-vegetated areas show patterns of splayed linear features (Figure 7c and 8c) probably resulting from yarding.

3.2.3 *Detail on Large Landslides*

High spatial resolution of the IKONOS and QUICKBIRD satellites allows identification of specific features of large landslides. Figure 9 shows a large rock fall imaged with IKONOS (Figure 9a), QUICKBIRD (Figure 9b), and 1: 15 000 colour aerial photography (Figure 9c). Detailed features visible on the satellite images include large blocks of debris (D), and gullies (G) on the slope surface. Due to greater spatial resolution and perception of three-dimensional

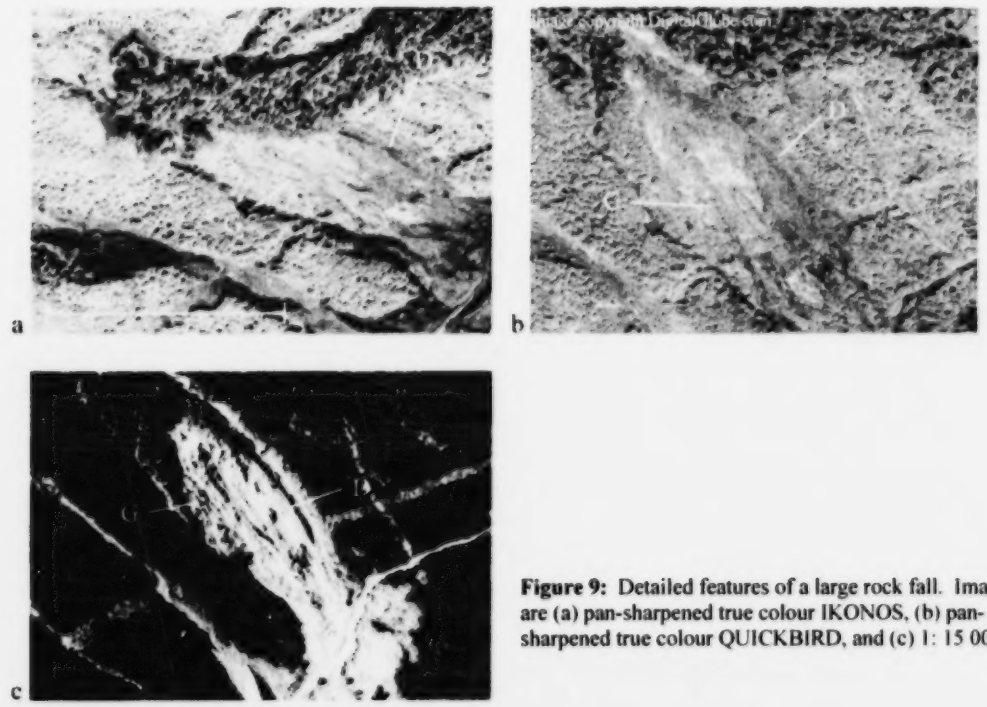

Figure 9: Detailed features of a large rock fall. Images are (a) pan-sharpened true colour IKONOS, (b) pan-sharpened true colour QUICKBIRD, and (c) 1: 15 000

colour aerial photograph. Features are: D – large blocks of debris; G – gullies.

morphology, aerial photography (e.g. Figure 9c) provided more information about detailed features on the rock fall. Both gullies and large debris were more obvious on aerial photographs interpreted by stereoscopic viewing than on the satellite imagery.

3.2.4 *Relict Landslides and Age Inference*

Vegetation initially colonizing disturbed soil may have different spectral and textural properties than vegetation on undisturbed soil. These differences can be used to identify relict landslides and possibly infer relative landslide age. Often, vegetation colonizing recently disturbed ground shows increased reflectance in the green and near infrared portions of the electromagnetic spectrum. Figure 10 shows a re-vegetated landslide on pan-sharpened colour infrared IKONOS (Figure 10a), and pan-sharpened colour infrared QUCIKBIRD (Figure 10b) images. The bright red colour of the re-vegetated landslide is due to its high reflectance in the near infrared (represented as red in colour infrared composites) relative to the surrounding vegetation.

Relict landslides are not, however, always identifiable based on spectral and textural differences. A relict landslide with vegetation cover that is spectrally and texturally similar to vegetation on adjacent terrain is shown in Figure 11. The relict landslide (R) is not apparent in either pan-sharpened colour infrared IKONOS (Figure 11a) or pan-sharpened colour infrared QUICKBIRD (Figure 11b) images. Initial detection of the relict landslide was by identification of morphological features (head scarp, depletion zone, and accumulation zone) during stereoscopic interpretation of 1: 15 000 colour aerial photographs. The relict slide can be inferred from the monoscopically viewed aerial photograph (Figure 11c) because suitable illumination conditions result in topographic shadowing of one side of the landslide depletion zone. A reactivated landslide (A) occurs in the depletion zone of another relict landslide, which was identified during stereoscopic interpretation of 1: 15 000 colour aerial photographs by recognition of the same morphological features described above. The reactivated landslide is evident in both the colour infrared IKONOS (Figure 11a) and colour infrared QUICKBIRD (Figure 11b) images, but not in the aerial photograph (Figure 11c). This suggests the landslide reactivated sometime between acquisition of the aerial photography (July 7, 1998; Table 2) and acquisition of the IKONOS scene (September 21, 2000; Table 1).

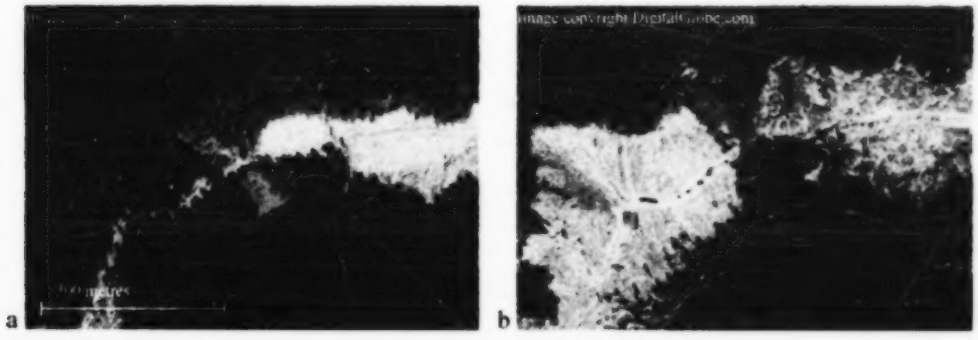

Figure 10: Re-vegetated relict landslide showing spectral and textural differences relative to surrounding vegetation. Images are (a) pan-sharpened colour infrared IKONOS and (b) pan-sharpened colour infrared QUICKBIRD.

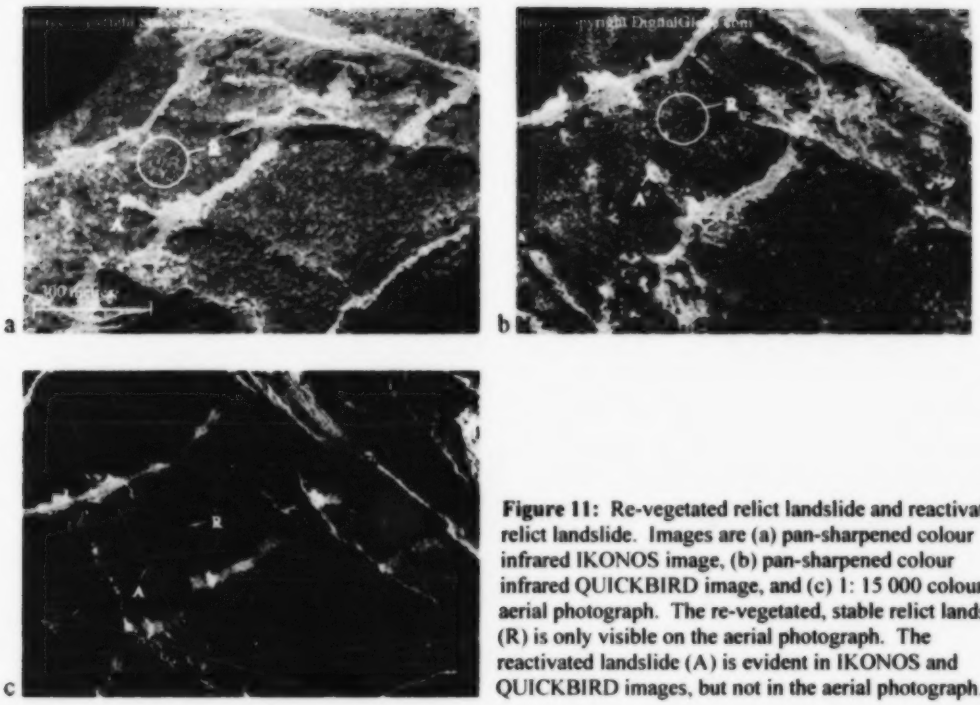

Figure 11: Re-vegetated relict landslide and reactivated relict landslide. Images are (a) pan-sharpened colour infrared IKONOS image, (b) pan-sharpened colour infrared QUICKBIRD image, and (c) 1: 15 000 colour aerial photograph. The re-vegetated, stable relict landslide (R) is only visible on the aerial photograph. The reactivated landslide (A) is evident in IKONOS and QUICKBIRD images, but not in the aerial photograph.

3.2.5 *Topographic Shadows*

Steep terrain increases the effects of topographic shadows, which can partially or entirely obscure landslides on shaded slopes. Topographic shadowing is a significant complication in landslide delineation due to the high frequency of slope failures in steep terrain. Effects of topographic shadows in 2.5 m SPOT imagery are shown in Figure 12. Roads and meander bars have similar reflectance properties to landslides and were observed to be similarly affected by topographic shadows. The meander bars (B) shaded by topography are especially obscured in the linear contrast stretched SPOT images (Figures 12a). Although the scene shown here appears dark, this enhancement provided high contrast between sunlit landslides and vegetation for the overall SPOT image. Meander bars are less obscured in the logarithmic contrast transformed SPOT image (Figure 12b). The road (R) is not identifiable in either SPOT image. Because of the illumination conditions present in the aerial photograph (Figure 12c) both the road and the meander bars are apparent.

IKONOS and QUICKBIRD scenes of a shadowed slope are shown in Figures 13 and 14, respectively. A pan-sharpened true colour, pan-sharpened colour infrared, and band ratioed image are shown for each sensor. Shadow effects are most noticeable on the colour images (Figures 13a and 14a). Visibility of un-vegetated terrain on shadowed slopes increases in the colour infrared images (Figures 13b and 14b) due to greater contrast between vegetated and un-vegetated surfaces. Band ratioed images (Figures 13c and 14c) greatly reduce the effects of variation in illumination and maximize the contrast between vegetated and un-vegetated ground. Shadow effects are less severe for QUICKBIRD colour and colour infrared images (Figures 14a and 14b) than for IKONOS colour and colour infrared images (Figures 13a and 13b). This probably results from slight differences in the spectral band widths used by each sensor.

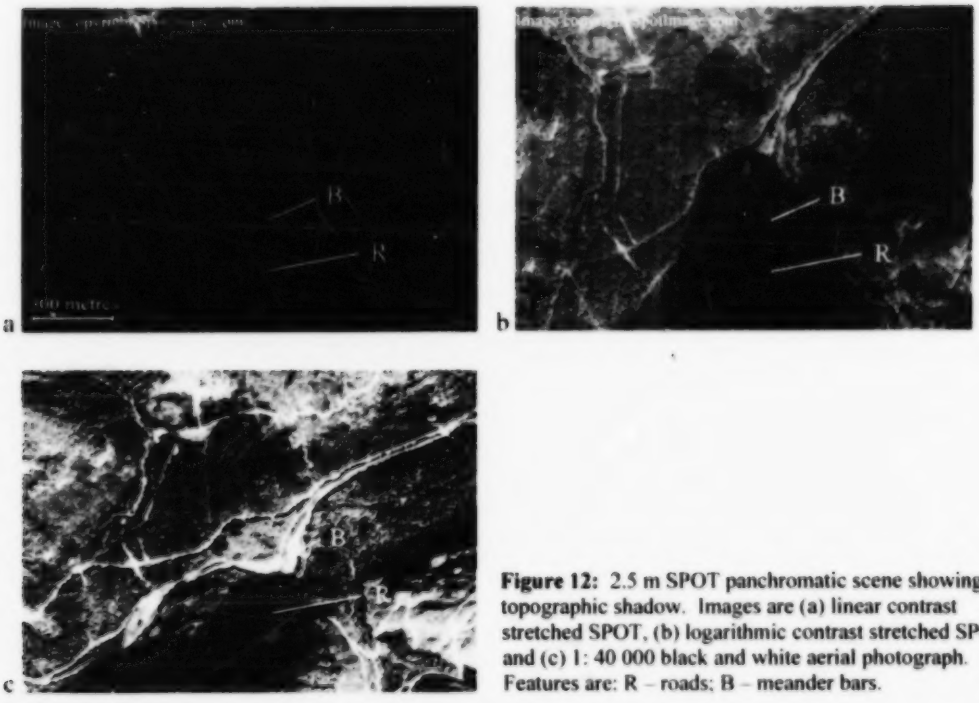

Figure 12: 2.5 m SPOT panchromatic scene showing topographic shadow. Images are (a) linear contrast stretched SPOT, (b) logarithmic contrast stretched SPOT, and (c) 1: 40 000 black and white aerial photograph. Features are: R – roads; B – meander bars.

Like orbital imagery, interpretation of aerial photography is hindered by topographic shadowing (Figure 13d and 14d). Digital image processing techniques cannot, however, be applied to photographic prints due to the analoge nature of these images. A lack of imaging in the near infrared portion of the electromagnetic spectrum for most forms of aerial photography further prevents use of the band ratio demonstrated here for shadow reduction in IKONOS and QUICKBIRD imagery.

Topographic shadowing is a function of sun azimuth and elevation, and, therefore, varies with time of day and season. Changes in sun position cause shadows in the large-scale aerial photography (Figures 13d and 14d) to occur on slopes of different aspect than those in the IKONOS and QUICKBIRD imagery.

3.3 Important Considerations in Landslide Detection

3.3.1 *Effects of re-vegetation on landslide detection*

Favourable climatic conditions for vegetation growth in southwest coastal British Columbia can result in rapid re-vegetation of landslides. Consequently, re-vegetation may begin to mask landslides soon after failure has occurred. The effect of re-vegetation on landslide detection must, therefore, be considered when comparing multi-date imagery separated by a significant time period. Due to the significant time lag between aerial photographs and satellite imagers evaluated here (between 2 and 7 years; see Tables 1 and 2) the ability of orbital imagery to detect landslides may be underestimated by comparison to pre-dating aerial photography.

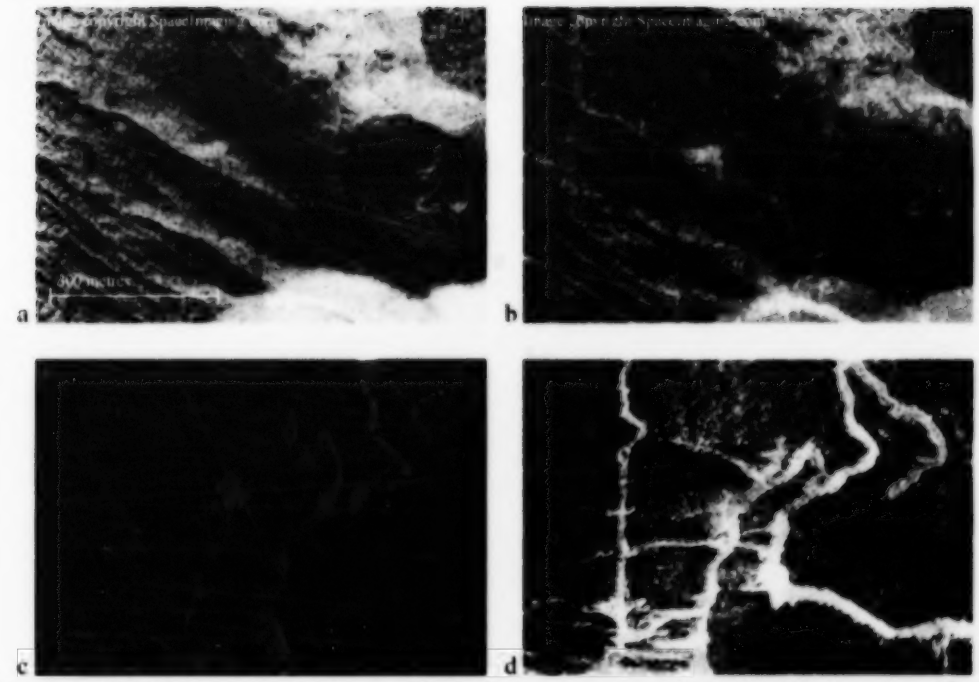

Figure 13: IKONOS scene showing topographic shadowing. Images are (a) pan-sharpened true colour, (b) pan-sharpened colour infrared, (c) band ratioed (Red/IR), and (d) 1: 15 000 colour aerial photograph.

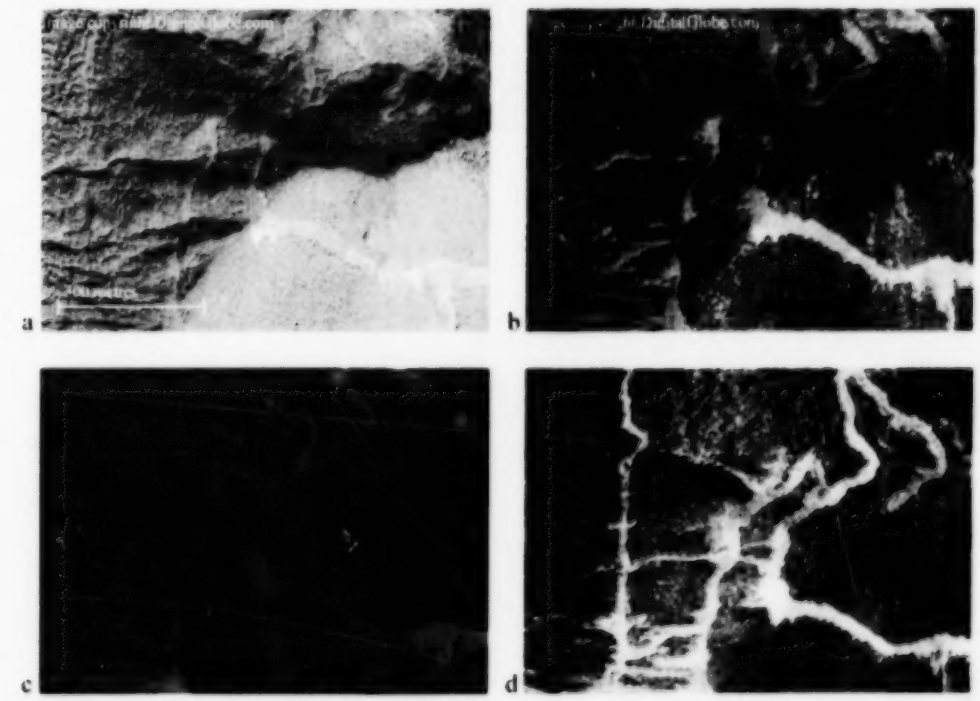

Figure 14: QUICKBIRD scene showing topographic shadowing. Images are (a) pan-sharpened true colour, (b) pan-sharpened colour infrared, (c) band ratioed (Red/IR), and (d) 1: 15 000 colour aerial photograph.

3.3.2 *Spatial resolution*

Spatial resolution of a sensor determines the minimum size of landslides that can be resolved. This minimum size is, however, also a function of scene contrast; smaller landslides are detectable on an imager showing greater contrast between landslides and adjacent terrain. Although imagery of a coincident area is not available for all orbital sensors discussed here, the effect of decreasing sensor resolution on landslide detection can be demonstrated by artificial means.

Figure 15 shows a panchromatic QUICKBIRD image resampled at spatial resolutions provided by various orbital sensors. Because all resampled images are derived from the same initial image the effects of spatial resolution only, without influence of changing target contrast, are shown. Resolutions and corresponding sensors evaluated in this study are: 0.61 m, QUICKBIRD panchromatic (Figure 15a); 1.0 m, IKONOS panchromatic (Figure 15b); 2.5 m SPOT panchromatic (Figure 15c); and 5.0 m SPOT panchromatic (Figure 15d). Spatial resolutions in Figure 15 are also provided for sensors previously evaluated for landslide detection: 10 m SPOT panchromatic (Coudert et al. 1990) and 30 m, Landsat TM (Sauchyn and Trench 1978).

As image resolution decreases, less information is conveyed about ground targets. The 0.61 m (Figure 15a) and 1.0 m (Figure 15b) resolution images appear similar because of the similarity of these resolutions. No noticeable loss in scene detail occurs for this change in spatial resolution at the scale shown in Figure 15. Some detail is lost in the 2.5 m resolution image (Figure 15c). Only the outlines of landslides are conveyed at this resolution. In the 5.0 m resolution image (Figure 15d) the scene has become pixelated. Larger landslides are represented as linear features composed of darker pixels, but smaller landslides are not detectable. No recognizable patterns representing landslides occur in either the 10 m (Figure 15e) or 30 m (Figure 15f) resolution images.

3.3.3 *Relationship between sensor resolution and area imaged*

The area covered by a single image decreases as sensor resolution increases. This trend is shown in Figure 1. The 5.0 m SPOT image covers a larger area than does the 2.5 m SPOT image, and the 2.5 m SPOT image covers a larger area than either the IKONOS or the QUICKBIRD image (each of which is composed of two adjacent scenes). The IKONOS and QUICKBIRD images cover a similar area as they have similar spatial resolution (Table 1). The approximate area covered in Figure 1 by a single 1: 15 000 aerial photograph is represented by a black dot.

The extensive area covered by a single SPOT image was found to allow rapid identification of obvious landslides. Appendix 1 is a single quadrant of the 2.5 m SPOT image and illustrates the ease with which orbital imagery can provide an overview of extensive areas. Detectable landslides are circled. The quadrant shown is divided into sub-quadrants for the purpose of display.

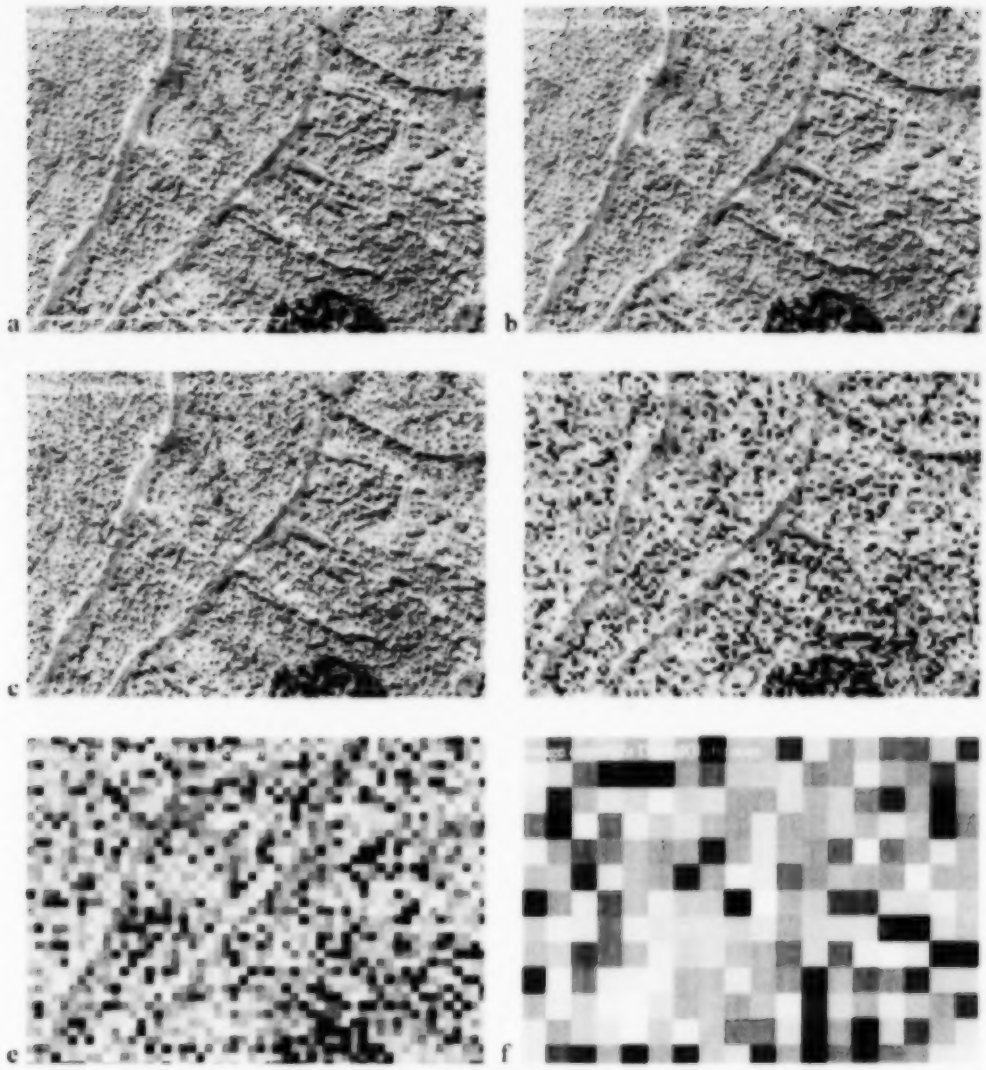

Figure 15: QUICKBIRD panchromatic image resampled at the resolution of various sensors. Images are (a) 0.61 m, QUICKBIRD panchromatic; (b) 1.0 m, IKONOS panchromatic; (c) 2.5 m SPOT panchromatic; (d) 5.0 m SPOT panchromatic; (e) 10 m SPOT panchromatic; and (f) 30 m, Landsat TM.

4 CONCLUSIONS

Based on an interpretation of the various forms of imagery shown in Tables 1 and 2, several conclusions can be made about the detection of landslides in southwest coastal British Columbia using remotely sensed imagery.

1) *Three qualities greatly improve the ability of a sensor for landslide detection:*
   - *High spatial resolution.*
   - *Multi-spectral data collection.*
   - *Stereoscopic viewing.*

Greater spatial resolution allows detection of smaller landslides. Multi-spectral imagery increases the selection of digital image processing techniques that may be applied to an image. Additionally, the use of near infrared data in image processing increases contrast between vegetated and un-vegetated ground and can provide reduction of topographic shadows. Stereoviewing allows perception of three-dimensional morphology. Three-dimensional morphology allows detection of landslides with surface cover characteristics similar to surrounding terrain and facilitates discrimination between landslides and other spectrally-similar un-vegetated surfaces.

2) *IKONOS and QUICKBIRD imagery out-performed SPOT imagery for landslide detection.*

This results from the improved spatial and spectral resolution provided by IKONOS and QUICKBIRD.

3) *The processed images allowing for optimal interpretation of IKONOS and QUICKBIRD scenes are colour infrared composites and band ratioed images.*

Band ratioing provides the greatest reduction of shadow effects. Colour infrared composites improve contrast between landslides and surrounding terrain, although to a lesser degree than band ratios, and preserve textural appearance of the imagery. The image interpreter is provided with the most information beneficial to landslide delineation when both colour infrared composites and band ratioed images are used.

4) *Despite multispectral imaging and high spatial resolution (relative to other satellites) IKONOS and QUICKBIRD did not allow delineation of all landslides visible on large-scale aerial photographs.*

5) *Increased aerial coverage provided by satellite images (relative to a single aerial photograph) improves ease of imagery reconnaissance.*

The large aerial coverage provided by a single satellite image is extremely beneficial when large areas need to be rapidly reviewed. In order to view the same area covered by one satellite image, multiple aerial photographs would need to be interpreted.

5 RECOMMENDATIONS

Knowledge obtained through this qualitative assessment of remotely sensed imagery can be used to improve future efforts to detect landslides in southwest coastal British Columbia. The following recommendations are made for future studies of remotely sensed imagery for landslide detection.

1) *Imagery used for landslide detection should combine three properties: high spatial resolution, multi-spectral data collection, and stereoscopic viewing.*

Such imagery will allow for perception of three-dimensional morphology of terrain, maximization of contrast between vegetated and un-vegetated surfaces, and reduction of shadow effect. This combination of requirements can only be met by large-scale, multispectral aerial photography.

2) A multi-scale approach to landslide investigations using satellite imagery and aerial photography could be used.

This approach would combine benefits of both spaceborne and airborne systems to allow landslide investigation at the terrain level and site specific level, respectively. Satellite imagery would provide an overview of large areas allowing identification of larger landslides and areas requiring further detailed investigation. Aerial photography would allow detailed investigation of small areas and detection of small or obscured landslides. Ideally, the aerial photography considered would be multispectral and digitally converted so that similar image enhancements could be applied at both the terrain and site specific level.

3) Ground truthing and quantitative accuracy assessment should be performed.

These are required to fully evaluate sensor performance for landslide detection and indicate the frequencies with which landslides are omitted and falsely identified. Large-scale aerial photography can be used as a means of pseudo-ground truth, as was done here. This is only logical where the imagery being evaluated is expected to perform less favourably than large-scale aerial photography, as is the case for all current orbital sensors. Pseudo-ground truth is not a replacement for field checking; field investigations are still required for proper accuracy assessment. The next step to be carried out in this project is ground truthing and quantitative accuracy assessment.

4) When evaluating the use of more than one sensor for landslide detection, imagery should be acquired over the same area and under the same imaging conditions.

These considerations facilitate direct multi-sensor comparisons. Consequently, the relative performance of different sensors can be evaluated.

5) Imagery should be acquired in or converted to a digital format.

Regardless of the source (airborne or spaceborne), the use of digital imagery increases the ways in which data can be used and manipulated.

- Digital imagery can be enhanced by numerous digital image processing techniques.
- Multi-temporal digital images can be used for automated change detection (e.g. Collins and Kliparchuk 2004).
- Once corrected for geometric distortions, digital image data can be combined with other spatial data for display purposes (e.g. overlay of vector data on imagery or creation of a 3-dimensional surface by draping of imagery over a DEM) or for input into GIS analysis.

6) If detailed spatial measurements are to be reliably derived form satellite data, metric accuracy of the sensor must first be evaluated.

Significant terrain distortions result from steep topography in which landslides commonly occur. Further complication results from off nadir viewing used by many orbital sensors (see Table 1 for view angles of orbital scene discussed here). Unlike aerial photography, the geometric distortions caused by orbital sensors are not well understood.

7) Successful methods should be replicated in other study areas.

Following quantitative accuracy assessment of landslide detection, the methods used should be extended to study areas in both similar and dissimilar environments. Replication in a study area with similar environmental conditions will demonstrate if methods are repeatable. Replication in a study area with different environmental conditions will demonstrate the applicability of methods under different terrain conditions.

6 ACKNOWLEDGMENTS

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APPENDIX 1: A Quadrant of the 2.5 m SPOT image showing detection of obvious landslides.